Effect of Poultry Diet on Phosphorus in Runoff from Soils Amended with Poultry Manure and Compost

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ABSTRACT

Phosphorus in runoff from fields where poultry litter is surface-applied is an environmental concern. We investigated the effect of adding phytase and reducing supplemental P in poultry diets and composting poultry manures, with and without Fe and Al amendments, on P in manures, composts, and runoff. We used four diets: normal (no phytase) with 0.4% supplemental P, normal + phytase, phytase + 0.3% P, and phytase + 0.2% P. Adding phytase and decreasing supplemental P in diets reduced total P but increased water-extractable P in manure. Compared with manures, composting reduced both total P, due to dilution of manure with woodchips and straw, and water-extractable P, but beyond a dilution effect so that the ratio of water-extractable P to total P was less in compost than manure. Adding Fe and Al during composting did not consistently change total P or water-extractable P. Manures and composts were surface-applied to soil boxes at a rate of 50 kg total P ha^{-1} and subjected to simulated rainfall, with runoff collected for 30 min. For manures, phytase and decreased P in diets had no significant effect on total P or molybdate-reactive P loads (kg ha^{-1}) in runoff. Composting reduced total P and molybdate-reactive P loads in runoff, and adding Fe and Al to compost reduced total P but not molybdate-reactive P loads in runoff. Molybdate-reactive P in runoff (mg box^{-1}) was well correlated to water-extractable P applied to boxes (mg box^{-1}) in manures and composts. Therefore, the final environmental impact of dietary phytase will depend on the management of poultry diets, manure, and farm-scale P balances.

POULTRY PRODUCTION is a major and growing industry in the United States (USDA National Agricultural Statistics Service, 2002). The increase in production over time has been necessarily accompanied by an increase in generated poultry litter, which is poultry excreta mixed with bedding material (e.g., sawdust, rice hulls, peanut hulls). Land-applied poultry litter can be a valuable source of crop nutrients, but exposure of recently applied litter to runoff can cause significant movement of nutrients, especially P, to the environment (Sharpley, 1997). When poultry litter is applied based on crop N requirements and litter N content, more P is applied than is typically removed in harvested crops (Sharpley, 1999). The long-term results are an accumulation of soil P (Sims et al., 2000) and an increased potential for P movement to the environment in surface runoff (Pote et al., 1999; Cox and Hendricks, 2000) or leaching (Heckrath et al., 1995; Novak et al., 2000). Controlling non-point-source P pollution is critical to reduce freshwater eutrophication and its deleterious effects on recreational and industrial uses of surface waters, and on drinking water quality (Carpenter et al., 1998).

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Poultry rations are mostly plant material, in which almost two-thirds of the P occurs in phytate molecules (Sebastian et al., 1998). Because poultry utilize at most one-third to one-half of phytate P (Sebastian et al., 1998), inorganic P is typically added to rations to meet dietary requirements. Although supplemental P is considered highly bioavailable, poultry may metabolize only 25 to 50% of it (Kornegay et al., 1996; Yi et al., 1996). The rest of the added P and other undigested P are excreted in manure. Throughout this paper, we refer to raw poultry excreta as poultry manure and manure mixed with bedding materials as poultry litter.

There has been a substantial effort to develop management practices to minimize P transfer to the environment following land application of poultry litter. One conceptually promising approach is addition of microbial phytase enzymes to poultry feeds. Ideally, phytase would increase the availability of phytate P to poultry, thus decreasing the need to add supplementary inorganic P to feed and decreasing total P concentrations in manure and litter. Less total P in poultry litter would decrease land-applied P in an N-based management plan, which should slow the rate of soil P accumulation and potential P transfer to the environment. Farms using a P-based plan could apply more litter without exceeding P loading goals.

Research results have been mixed regarding the effect of phytase and reduced P in poultry rations on P concentrations in manure or litter and P in runoff after their application to soils. Several studies show that adding phytase and decreasing dietary P can decrease total P excreted by birds and total P concentrations in litter (Perney et al., 1993; Yi et al., 1996; Fergusen et al., 1998; Yan et al., 2000). Moore et al. (1998) showed that adding phytase and decreasing inorganic P in poultry rations did not significantly decrease total or water-extractable P in litter. When this litter was land-applied, total P concentrations in runoff were not significantly less than in runoff from plots receiving litter from a no-phytase diet. Saylor et al. (2001) reported that adding phytase and reducing inorganic P from 0.43 to 0.33% decreased total P but not water-extractable P in the litter. Reducing inorganic P to 0.23% decreased both litter P forms. DeLaune et al. (2001) land-applied the litter of Saylor et al. (2001) and found that dissolved P in runoff was greatest from plots with litter from the phytase and reduced-P diets.

Overall, the literature is unclear if adding phytase to poultry diets will always reduce P concentrations in manures and litters or P concentrations in runoff from manure- or litter-treated soils. The first objective of this research was to investigate the effect of adding phytase and reducing supplemental P in poultry diets on P concentrations in manure and P in runoff from soils to which these manures were surface-applied. The second objective was to compost the manures, with and without additions of Fe and Al before composting, and investigate the effect of composting on P concentrations in composts and P in runoff.

MATERIALS AND METHODS

Poultry Feeding Trials and Composting of Poultry Manure

Battery-cage trials without bedding materials were conducted for 6 wk with male broiler chicks. Four diet treatments were replicated 12 times, with diets including: a normal (no-phytase) diet with 0.4% average supplemental P; a normal plus phytase diet (Allzyme Phytase, 11 500 PTU kg^{-1}; Alltech, Nicholasville, KY); a phytase diet with 0.3% supplemental P; and a phytase diet with 0.2% supplemental P. These phytase units are used by the Alltech in-house bioassay for phytase activity and the ability of birds to metabolize phytate, and are similar to typical phytase rates reported in the literature. Starter rations were fed from 0 through 3 wk, and grower rations from 3 through 6 wk (Tables 1 and 2). Feed and water were offered ad libitum, and weekly feed intake and body weights of chicks were similar for all treatment groups. Manure samples from each diet replication were collected every other day and frozen. After the feeding trial, frozen samples from each diet replication were thawed in a refrigerator and bulked over time by homogenization in a low-speed mixer to produce a final manure representative of the entire 6-wk trial. The 12 replicates were reduced to triplicates by combining excreta from four randomly selected replicates.

Samples of the three manure replications for each diet were composted by combining three volumes woodchips, two volumes manure, and one volume orchard grass straw. Ingredients were mixed, placed into a stainless steel mesh cylinder, and mounted in a self-heating laboratory composter (Sikora et al., 1983). Mixtures were composted with and without drinking water treatment sludge to add Al or Fe-rich sludge from titanium oxide production to add Fe, as described by Dao et al. (2001). In our study, 2 mol of Fe or Al were added for each mole of water-extractable P in manure, which meant Fe-rich sludge was added at a rate of 28 g kg^{-1} of manure mixture and water treatment sludge at 37 g kg^{-1} mixture. Dao et al. (2001) added more Fe and Al amendments because additions were based on total P concentrations of their poultry litter. All three manure replications were composted separately, and a typical composting run continued until at least two of the three replicate composters cooled to near room temperature, which was approximately 30 d.

In total, there were 12 manure samples from three replications of four diet treatments, and 36 compost samples from the 12 manure samples being composted with and without Fe or Al amendments. Manures and composts were stored at −10°C when not in use for analysis or application to runoff boxes. Wet manures and composts were analyzed for total P by Kjeldahl digestion and water-extractable P as outlined in Pierzynski (2000). Solutions were analyzed for P by the method of Murphy and Riley (1962). The water extraction used a water to wet material ratio of 10:1 (water to dry manure of about 40:1 and water to dry compost of about 20:1), a shaking time of 30 min, and filtering through 0.45-μm filters. These conditions will not extract the maximum amount of water-extractable P from manures or composts (Kleinman et al., 2002; Vadas et al., 2004). However, Kleinman et al. (2002) showed that the amount of P extracted at these water to manure ratios and shaking time should be well related to molybdate-reactive P concentrations in runoff from soils where manures are surface-applied.

Table 1. Formulations of poultry diets that were fed from 0 through 3 wk of age.

Ingredient	Diet: Normal + 0.4P	Phytase + 0.4P†	Phytase + 0.3P	Phytase + 0.2P
	%			
Ground yellow corn	52.0	52.0	53.1	54.1
Soybean meal (47.5%)	39.2	39.2	39.1	38.9
DL-methionine (99%)	0.2	0.2	0.2	0.2
Limestone	1.3	1.3	1.4	1.4
Dicalcium phosphate	1.8	1.8	1.3	0.7
NaCl	0.3	0.3	0.3	0.3
Copper sulfate	0.1	0.1	0.1	0.1
Choline chloride	0.1	0.1	0.1	0.1
Animal vegetable fat blend	4.3	4.3	4.0	3.6
Sodium bicarbonate	0.3	0.3	0.3	0.3
Trace mineral mixture‡	0.1	0.1	0.1	0.1
Vitamin mixture§	0.1	0.1	0.1	0.1
	Nutrient composition			
Calculated				
ME, kcal kg^{-1}	3100	3100	3100	3100
Protein	22.8	22.8	22.8	22.8
Calcium	1.0	1.0	0.9	0.8
Available phosphorus	0.5	0.5	0.4	0.3
Analyzed				
Protein	20.9	20.9	22.4	23.7
Calcium	1.0	1.0	1.0	0.7
Phosphorus (total)	0.5	0.5	0.4	0.3

† Phytase diets were mixed to contain 11 500 PTU kg^{-1} phytase (Allzyme Phytase; Alltech, Nicholasville, KY). The normal diet contained no phytase.
‡ Trace mineral mixture contains 3.2% iron (from ferrous sulfate), 0.4% copper (from copper sulfate), 9.6% manganese (from manganese sulfate), 11.2% zinc (from zinc sulfate), 0.16% iodine (from calcium iodate), and 0.050% selenium (from selenium mix).
§ Vitamin mixture supplies (per pound of premix) 10 000 000 IU vitamin A, 4 500 000 IU vitamin D3, 40 000 IU vitamin E, 15 mg vitamin B12, 9 g riboflavin, 80 g niacin, 18 g pantothenic acid, 2 g menadione acetate, 2.2 g folic acid, 3 g thiamine mononitrate, 4.7 g pyridoxine, and 0.2 g biotin.

Table 2. Formulations of poultry diets that were fed from 4 through 6 wk of age.

	Diet			
Ingredient	**Normal + 0.4P**	**Phytase + 0.4P†**	**Phytase + 0.3P**	**Phytase + 0.2P**
	%			
Ground yellow corn	**58.8**	**58.8**	**59.9**	**61.0**
Soybean meal (47.5%)	**33.1**	**33.1**	**32.9**	**32.8**
DL-methionine (99%)	**0.2**	**0.2**	**0.2**	**0.2**
Limestone	**1.4**	**1.4**	**1.4**	**1.5**
Dicalcium phosphate	**1.3**	**1.3**	**0.8**	**0.2**
NaCl	**0.3**	**0.3**	**0.3**	**0.3**
Copper sulfate	**0.1**	**0.1**	**0.1**	**0.1**
Choline chloride	**0.1**	**0.1**	**0.1**	**0.1**
Animal vegetable fat blend	**4.2**	**4.2**	**3.8**	**3.4**
Sodium bicarbonate	**0.3**	**0.3**	**0.3**	**0.3**
Trace mineral mixture‡	**0.1**	**0.1**	**0.1**	**0.1**
Vitamin mixture§	**0.0**	**0.0**	**0.0**	**0.0**
	Nutrient composition			
Calculated				
ME, kcal kg^{-1}	**3150**	**3150**	**3150**	**3150**
Protein	**20.4**	**20.4**	**20.4**	**20.4**
Calcium	**0.9**	**0.9**	**0.8**	**0.7**
Available phosphorus	**0.4**	**0.4**	**0.3**	**0.2**
Analyzed				
Protein	**22.4**	**22.4**	**22.5**	**21.4**
Calcium	**0.9**	**0.9**	**0.8**	**0.8**
Phosphorus (total)	**0.4**	**0.4**	**0.3**	**0.2**

† Phytase diets were mixed to contain 11 500 PTU kg^{-1} phytase (Allzyme Phytase; Alltech, Nicholasville, KY). The normal diet contained no phytase.
‡ Trace mineral mixture contains 3.2% iron (from ferrous sulfate), 0.4% copper (from copper sulfate), 9.6% manganese (from manganese sulfate), 11.2% zinc (from zinc sulfate), 0.16% iodine (from calcium iodate), and 0.050% selenium (from selenium mix).
§ Vitamin mixture supplies (per pound of premix) 15 000 000 IU vitamin A, 6 400 000 IU vitamin D3, 40 000 IU vitamin E, 20 mg vitamin B12, 11 g riboflavin, 116 g niacin, 21 g pantothenic acid, 4 g menadione acetate, 1.75 g folic acid, 2.25 g thiamine mononitrate, 4.4 g pyridoxine, and 0.1 g biotin.

Runoff Experiments

Soil Box Preparation and Soil Analysis

A Mattapex silt loam (fine-silty, mixed, mesic, Aquic Hapludult) collected from 0 to 20 cm from the Wye Research and Education Center in Queenstown, MD, was air-dried and crushed to pass a 2-mm sieve. The soil had an organic matter concentration of 2.1%, a pH of 5.8 (1:1 soil to water ratio), water-extractable P of 6.9 mg kg^{-1}, and Mehlich-3 P of 139 mg kg^{-1}, as estimated by methods of Pierzynski (2000). Phosphorus in water and Mehlich-3 extracts was determined by the method of Murphy and Riley (1962). Soil was packed into wooden runoff boxes to a depth of 7.5 cm. Runoff boxes were 100 cm long by 35 cm wide by 15 cm deep and had three 1-cm-diameter drain-holes in the bottom and a 13-mm-diameter drain-port in the front that allowed collection of surface runoff (Isensee and Sadeghi, 1999). Corn residue was spread onto boxes at a rate of 150 g box^{-1}, which is equivalent to residue left from a corn harvest of 8.7 m^3 ha^{-1} (100 bushels acre^{-1}). Residue had been chopped and sieved to obtain fairly uniform, approximately 3-cm pieces, and had been subjected to several wetting and drying cycles to leach out P and minimize its contribution to runoff.

Runoff Experiments and Analysis

Background, pretreatment runoff experiments were conducted for all soil boxes to estimate P release from soil and corn residue. Boxes were placed at a 5% slope under a rain simulator, which consisted of a round, rotating table 2.4 m in diameter with four dripper systems placed every 90° at 1.5 m above the boxes (Isensee and Sadeghi, 1999). Drippers applied rain at 70 mm h^{-1}. These slope and rain conditions were consistent with those of the National P research project (National Phosphorus Research Project, 2003). Soil boxes were pre-wet 2 d before runoff experiments by applying rain just until runoff was initiated. Runoff was collected over 5-min intervals for 30 min and was analyzed for volume, sediment concentration by evaporation, dissolved P after filtration through 0.45-μm filters, total dissolved P after the same filtration and acid persulfate digestion, and total P by acid persulfate digestion without filtration. All solutions were analyzed for P by the method of Murphy and Riley (1962). The digestion procedure was modified from that of Rowland and Haygarth (1997) by increasing the concentrations of acid and persulfate to give maximum recovery of P in samples while providing no interference with the colorimetric procedure of Murphy and Riley (1962).

Two days after background runoff experiments, manures and composts were surface-applied to boxes at the rate of 50 kg total P ha^{-1}, which approximates a typical application rate of a P-based management plan. This rate resulted in manure and compost applications ranging from 10 to 20 Mg ha^{-1}. Even though many producers apply poultry litter based on litter N content and crop N needs, a P-based application rate was chosen due to manure quantity restraints, and to allow P runoff results to be more comparable across treatments. Due to restraints on numbers of runoff boxes and soil quantity, only two of the three bulked diet replications of manures and composts were used in the runoff experiments. Runoff experiments for manure- or compost-amended soils were conducted and runoff samples analyzed for P as described above.

When using 0.45-μm filters, the Murphy and Riley (1962) procedure will not measure strictly dissolved inorganic P in solution. There is likely to be acid-mediated hydrolysis of dissolved organic compounds and sorption or desorption of P from colloidal material. McDowell and Sharpley (2001) found that after filtering soil water extracts with 0.45-μm filters, 15 to 75% of nondissolved inorganic P in solutions was measured by the Murphy and Riley (1962) procedure, resulting in an average overestimation of dissolved inorganic P of 12.5%. They concluded that colloidal material did not affect P measured in solutions. Similarly, Haygarth et al. (1997) saw no significant difference for P measured in soil leachate or runoff samples by the Murphy and Riley (1962) procedure after filtering with filters ranging from 0.45 to 0.025 μm, suggesting that colloidal P did not affect P measurement. In our runoff samples, P measured after filtering and digestion was consistently about 13% greater than after filtering alone, which is similar to the trends of McDowell and Sharpley (2001). Sharpley and Moyer (2000) found that for water extracts of poultry manure, the difference in P measured after filtering and digestion was consistently about 24% greater than after filtering alone. We did not estimate such a difference for our poultry manures, but it is likely to be similar. These differences of 13 and 24% are not extreme, which suggests that the maximum source of P overestimation in the Murphy and Riley (1962) procedure for our undigested runoff and manure water extraction samples was also not extreme. Therefore, it is likely that the majority of P measured in our samples by the Murphy and Riley (1962) procedure was indeed dissolved inorganic P. We use the terms "water-extractable P" for manure water extractions, "molybdate-reactive P" for runoff samples that were filtered but not digested, and "total dissolved P" for runoff samples that were filtered and digested.

Statistical Analysis

In our statistical analysis of data, the primary interest was the effect of poultry diet on P in manure and runoff. Afterwards were interests in how composting affected P in manures and runoff, and how Fe and Al amendments during composting affected P in composts and runoff. Therefore, only select groups of data were statistically compared to match these interests. Statistical *t* tests were conducted to determine the effect of the four poultry diets on P concentrations in manures, the effect of composting on P concentrations in composts by comparing only manures and unamended composts, and the effect of adding Fe or Al before composting by comparing only Fe- and Al-amended composts and unamended composts. The same comparisons were made for runoff data. When a statistically significant effect was determined for these three main comparisons, an LSD value was calculated. All statistical procedures were performed using the SAS Version 8 system (SAS Institute, 1999).

RESULTS AND DISCUSSION

Phosphorus Characteristics of Manures

Adding phytase without reducing supplemental P did not significantly decrease manure total P, but adding phytase and reducing P did decrease manure total P (Table 3). Adding phytase without reducing supplemental P significantly increased manure water-extractable P compared with the no-phytase diet (Table 3). Reducing supplemental P in phytase diets decreased water-extractable P, but to concentrations still greater than in the no-phytase diet manure. These trends in manure P resulted in the greatest water-extractable P to total P ratio in the manures from the phytase diets (Table 3).

Several studies have investigated the effect of phytase and supplemental P in poultry diets on manure or litter total P (Perney et al., 1993; Yi et al., 1996; Fergusen et al., 1998; Moore et al., 1998; Yan et al., 2000; Saylor et al., 2001; Toor et al., 2003), with some consistent trends despite differences in feeding trials, diets, waste characteristics with and without bedding materials, and analytical techniques. Adding phytase without P reductions to poultry rations or with conservative P reductions (e.g., from 0.4 to 0.3% supplemental P) may not consistently decrease total P in manure or litter. However, adding

Table 3. Moisture content, concentrations of total phosphorus (TP) and water-extractable phosphorus (WEP), and the ratio of WEP to TP for poultry manure, composted manure, and Fe- and Al-amended composted manure from feeding trials using four diets containing phytase and different concentrations of supplemental P.

Material	Diet	Moisture	TP	WEP	WEP/TP
		%	— mg kg^{-1} dry material —		
Raw manure	normal + 0.4P	76.3	20 405	5 195	0.25
	phytase + 0.4P	76.4	16 220	8 435	0.53
	phytase + 0.3P	77.8	15 855	7 696	0.49
	phytase + 0.2P	77.0	11 278	7 424	0.66
	diet effect†	NS	*	*	**
	LSD‡	–	4 369	1 636	0.14
Composted manure	normal + 0.4P	56.7	8 025	950	0.12
	phytase + 0.4P	58.7	9 408	896	0.09
	phytase + 0.3P	66.7	11 188	1 210	0.11
	phytase + 0.2P	59.0	8 165	850	0.11
	compost effect§	***	***	***	***
	LSD¶	2.4	2 619	894	0.11
Fe-amended composted manure	normal + 0.4P	67.8	10 357	898	0.09
	phytase + 0.4P	51.0	8 062	617	0.08
	phytase + 0.3P	55.6	7 875	867	0.11
	phytase + 0.2P	55.2	5 490	473	0.09
Al-amended composted manure	normal + 0.4P	40.2	8 540	510	0.06
	phytase + 0.4P	37.1	8 953	579	0.07
	phytase + 0.3P	39.6	6 353	863	0.14
	phytase + 0.2P	34.5	7 362	576	0.08
	amendment effect#	***	NS	***	NS
	LSD††	6.1	–	147	–

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Statistical significance (*t* test) of effect of poultry diet for the four raw manures.
‡ Least significant difference value for four raw manures if effect of diet was statistically significant.
§ Statistical significance (*t* test) of effect of composting between four raw manures and four unamended composts.
¶ Least significant difference value for four raw manures and four unamended composts if effect of composting was statistically significant.
# Statistical significance (*t* test) of the effect of adding Fe or Al during composting for 12 different composts.
†† Least significant difference value for 12 composts if effect of Fe or Al amendments in composts was statistically significant.

phytase with greater P reductions (e.g., from 0.4 to 0.2% supplemental P) generally decreases manure or litter total P.

Fewer studies have monitored changes in water-extractable P in poultry litter or manure from different diets (Stanley, 2001; Moore, 2003; Toor et al., 2003). Moore et al. (1998) reported that adding phytase and decreasing inorganic P by approximately 15% in diets did not change water-extractable P in litter. Saylor et al. (2001) showed that adding phytase and decreasing inorganic P from 0.43 to 0.33% did not change litter water-extractable P, but that adding phytase and decreasing supplemental P to 0.23% significantly decreased litter water-extractable P. Based on these limited data and our own, adding phytase and reducing inorganic P, even at higher rates of P reduction, apparently does not always decrease manure water-extractable P.

Storage and handling can influence poultry manure or litter water-extractable P. DeLaune et al. (2001) measured water-extractable P in the litters from Saylor et al. (2001) after they had been deep-stacked for 6 to 8 mo. They found that water-extractable P in the litter from the phytase + 0.33% P diet had increased to concentrations greater than in the no-phytase diet litter, which agrees with our results. We measured water-extractable P in manures at collection and again before runoff experiments, between which times the samples had gone through a few freeze–thaw cycles and a room temperature mixing and compositing. Water-extractable P in manure at collection averaged 52% less than just before runoff studies. However, trends for the effect of diet on water-extractable P were the same at both analysis times. Codling et al. (2000) monitored changes in water-extractable P in poultry litter incubated at 25°C for 7 wk. Water-extractable P increased from an initial concentration of 3.9 to 5.2 g kg^{-1} after 2 wk, decreased to 4.3 g kg^{-1} after 4 wk, and then increased again to 5.9 g kg^{-1} after 7 wk. This 34% increase in water-extractable P over 7 wk is similar to the trend observed with our manures. Therefore, water-extractable P in poultry litters or manures is a dynamic parameter affected by storage and handling as well as original poultry diet or other treatments.

Phosphorus Characteristics of Composts

The total P concentration of manures decreased by about 50% before composting due to dilution with the low P composting materials (data not shown). After composting, total P concentrations of the mixtures increased about 20% from the starting mixture because of loss of carbon during composting, but conservation of P. Composting resulted in a product that had concentrations of 42% less total P, 86% less water-extractable P, and a 77% less water-extractable P to total P ratio than manures (Table 3). Sharpley and Moyer (2000) also found that composting poultry manure decreased total P by 67% and water-extractable P by 73%. However, DeLaune et al. (2000) found that composting poultry litter without amendments increased total P by 44% and water-extractable P by 160%, due to loss of mass and conservation of P during composting. Dao et al. (2001) found that composting poultry litter did not affect water-extractable P.

Compared with unamended composts, adding Fe and Al amendments before composting did not significantly affect total P concentrations, but significantly decreased water-extractable P of the final composts by approximately 30% (Table 3). DeLaune et al. (2000) also found that adding alum to poultry litter on an 11:1 molar basis of total Al to litter water-extractable P, which is greater than in our study, and composting the mixture had little effect on total P, but decreased water-extractable P by 93%, compared with unamended composts. Dao et al. (2001) added Fe or Al from the same sources as in our study to poultry litter on a 18:1 molar basis of total Fe or Al to litter water-extractable P, which is also greater than in our study. Dao et al. (2001) observed that adding Fe or Al reduced water-extractable P concentrations of compost mixtures before composting, but the composting process itself had no further effect on water-extractable P.

Overall, composting poultry manure or litter with amendments as a carbon source can decrease both total and water-extractable P in the final product. Adding Fe and Al before composting will probably have little effect on total P, but will decrease water-extractable P in the final compost product. However, composting poultry litter alone with no carbon amendments can increase both total and water-extractable P in the final product. Therefore, the method of composting, rate of amendments, and maturity of compost probably play a significant role in the total and water-extractable P concentration of the final product (Pruesch et al., 2002).

Runoff Volumes and Sediment Transfer in Runoff Experiments

Our rainfall simulation conditions represent a "worst case" scenario in which an already wet soil receives poultry manure or compost, and then receives a 30-min, 70 mm h^{-1} rainfall event. Therefore, the runoff data are most useful for making relative comparisons among treatments, and should be used cautiously when discussing likely P transfer under actual field conditions.

Total runoff was consistent for all soil boxes and averaged 8.4 L (Table 4), compared with 12.3 L of total rain. Runoff generally increased with time as soils became wetter. For background experiments, sediment concentrations (g L^{-1}) in runoff tended to decrease and loads (kg ha^{-1}) tended to increase with time. Sediment concentrations and loads from manure-treated boxes increased for the first 10 to 15 min, and then decreased thereafter. For compost-treated boxes, sediment concentrations decreased with time, while sediment loads tended to increase for the first 5 to 10 min and then decrease thereafter. Overall, sediment concentrations and loads in runoff were least for background boxes, greatest for manure-treated boxes, and in between for compost-amended boxes (Table 4), showing that manure and compost materials themselves comprised some

Table 4. Cumulative quantities of molybdate-reactive phosphorus (MRP), total dissolved phosphorus (TDP), and total phosphorus (TP) lost from soil.

Treatment	Diet	Runoff	Sediment yield	MRP	TDP	TP
		L	kg ha^{-1}			
Background		7.7	378	0.13	0.14	0.63
Raw manure	normal + 0.4P	9.2	1273	6.9	9.1	25.9
	phytase + 0.4P	8.9	1291	8.8	9.5	26.9
	phytase + 0.3P	8.6	1372	10.5	12.0	24.0
	phytase + 0.2P	8.1	1782	12.0	13.0	27.7
	diet effect†	NS	NS	NS	NS	NS
	LSD‡	–	–	–	–	–
Composted manure	normal + 0.4P	9.0	1053	2.7	4.2	15.7
	phytase + 0.4P	8.9	756	2.0	3.2	12.7
	phytase + 0.3P	9.7	803	2.1	3.4	15.8
	phytase + 0.2P	8.6	744	2.0	3.1	9.6
	compost effect§	NS	**	***	***	**
	LSD¶	–	300	2.4	2.3	6.4
Fe-amended composted manure	normal + 0.4P	8.8	959	2.0	2.4	15.5
	phytase + 0.4P	8.7	634	1.8	2.1	9.4
	phytase + 0.3P	9.2	885	2.3	2.7	8.2
	phytase + 0.2P	9.3	912	2.1	2.1	8.2
Al-amended composted manure	normal + 0.4P	9.4	698	1.8	2.0	7.6
	phytase + 0.4P	9.2	511	2.2	2.4	6.9
	phytase + 0.3P	9.3	689	3.2	3.5	8.6
	phytase + 0.2P	8.7	811	2.3	2.8	6.6
	amendment effect#	NS	NS	NS	**	**
	LSD††	–	–	–	0.7	3.0

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Statistical significance (*t* test) of effect of poultry diet for the four raw manures.
‡ Least significant difference value for four raw manures if effect of diet was statistically significant.
§ Statistical significance (*t* test) of effect of composting between four raw manures and four unamended composts.
¶ Least significant difference value for four raw manures and four unamended composts if effect of composting was statistically significant.
# Statistical significance (*t* test) of the effect of adding Fe or Al during composting for 12 different composts.
†† Least significant difference value for 12 composts if effect of Fe or Al amendments in composts was statistically significant.

of the runoff sediment, with manure contributing more than compost.

General Trends for Phosphorus in Runoff

For all boxes, molybdate-reactive P concentrations in runoff were strongly related ($r^2 = 0.97$) to total dissolved P (data not shown). Molybdate-reactive P was about 13% less than total dissolved P, indicating that about 10% of the total dissolved P was probably in the organic form. Total P concentrations in runoff were about three times greater than molybdate-reactive P (Fig. 1a) and were related to sediment concentrations (Fig. 1b), indicating that a large proportion of runoff P was associated with sediment. Runoff molybdate-reactive P was not related to sediment concentrations for background ($r^2 = 0.06$) experiments, but was fairly well related for manure ($r^2 = 0.49$) and compost ($r^2 = 0.52$) experiments (data not shown). This suggests that manure and compost material, but not soil material, in runoff released P during or after runoff collection.

For background experiments, all runoff P concentrations (mg L^{-1}) decreased steadily with time (Fig. 2a). However, P loads (kg ha^{-1}) were constant with time, showing that concentration decreases were probably a result of dilution with greater runoff water. All P concentrations in runoff from manure-treated boxes were one to two orders of magnitude greater than from background boxes (Fig. 2b vs. 2a). Unlike background experiments, molybdate-reactive P concentrations increased for the first 10 min of runoff, and then decreased steadily thereafter (Fig. 2b). Molybdate-reactive P loads also increased for the first 10 min of runoff, but then remained constant thereafter. Trends were similar for total P and total dissolved P concentrations and loads (data not shown).

The time course of manure runoff molybdate-reactive P concentrations and loads can be attributed to characteristics of P release from manures and the consistency of manures, which required application as small clumps over the soil surface. These clusters broke down physically during runoff until the manure was evenly distributed at the end of the 30-min rainfall. As these clumps broke down with time, the amount of rain interacting with manure probably increased, thus increasing P release from manures (Kleinman et al., 2002; Vadas et al., 2004). This corresponded to increasing P concentrations and loads early in runoff, even though runoff volumes were increasing and the overall amount of water-extractable P in manures was probably decreasing (Sharpley and Moyer, 2000). Fairly constant molybdate-reactive P loads in runoff during the latter half of runoff can be attributed to decreasing P concentrations but increasing runoff volumes. This in turn means that P release from manures was fairly constant. This constant P release could be attributed to a canceling effect of an increase in manure P release due to greater rainfall and manure interaction, but a decrease in manure P release due to less water-extractable P remaining in manure.

All P concentrations in runoff from compost-treated boxes were about half of those for manure-treated boxes, but still an order of magnitude greater than those for background boxes (Fig. 2c). Both molybdate-reac-

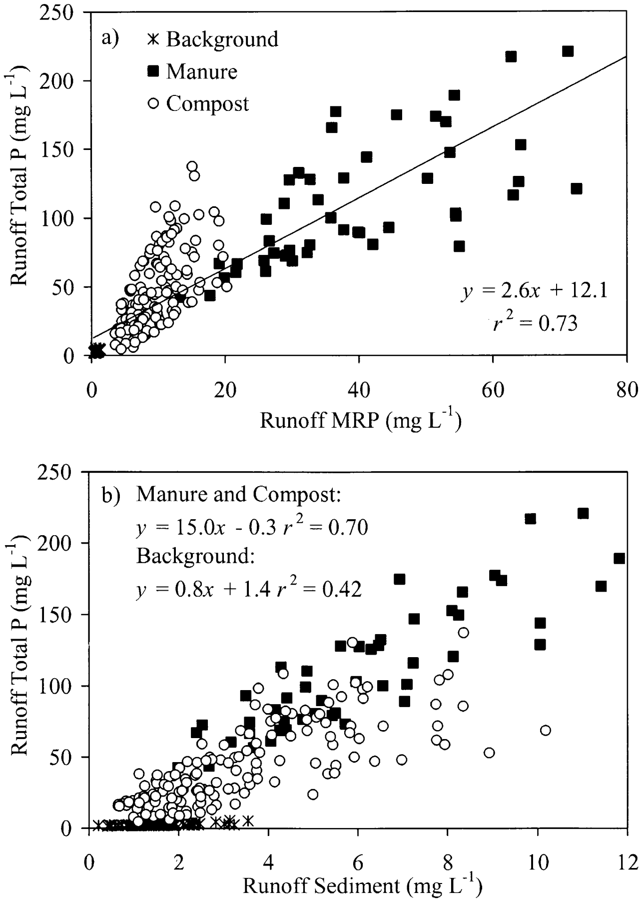

Fig. 1. Relationships between (a) molybdate-reactive phosphorus (MRP) and total P in runoff, and (b) sediment concentration and total P in runoff from all soil boxes during 30 min of runoff.

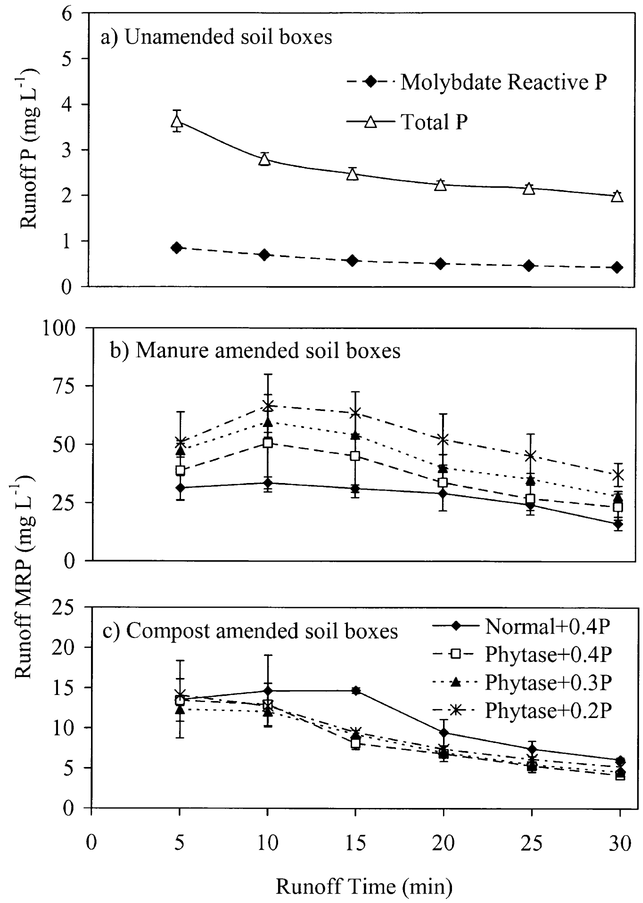

Fig. 2. (a) Average runoff molybdate-reactive phosphorus (MRP) and total P concentrations from background soil boxes, and average runoff MRP concentrations from (b) soil boxes with manure and (c) compost treatments during 30 min of runoff.

tive P concentrations and loads were greatest for the first 5 to 10 min of runoff and then decreased steadily thereafter (Fig. 2c). Runoff total P and total dissolved P concentrations and loads paralleled these trends in molybdate-reactive P. These runoff P patterns were also observed for the Fe- and Al-amended composts (data not shown). Contrary to manures, the time course of runoff P concentrations and loads for the composts suggests that overall P release from composts decreased steadily with time. The consistency of the composts allowed a more uniform distribution over the soil surface than for the manures. Therefore, there were few clumps to break down, and rainfall and compost interactions were more consistent over time.

Effect of Poultry Diet on Phosphorus in Runoff

There were no significant differences in total P loads (kg ha^{-1}) in runoff among any of the manure treatments (Table 4). This is reasonable since all manures were applied to boxes at the same rate of manure total P. Diet did not significantly affect molybdate-reactive P or total dissolved P loads in runoff, although there were strong trends for molybdate-reactive P to increase as phytase was added and dietary supplemental P was decreased. Because all manures were applied to boxes at 50 kg total P ha^{-1} and because the water-extractable P to total P ratio differed among diets (Table 3), the mass of water-extractable P applied in the manures also differed among diets, and even among diet replications. Overall, molybdate-reactive P in runoff was significantly related (r^2 = 0.92) to water-extractable P applied to boxes in manures and composts (Fig. 3). These results are consistent with research showing that when litters or manures are surface-applied to soils, molybdate-reactive P in runoff soon after application is controlled by the amount of water-extractable P applied (Kleinman et al., 2002; Sauer et al., 2000; Shreve et al., 1995; Vadas et al., 2004).

Few studies have investigated the effect of poultry diet on P transfer in runoff (Moore, 2003). Moore et al. (1998) saw that a phytase plus reduced-inorganic P diet did not significantly decrease total or water-extractable P in broiler litter compared with litter from a conventional no-phytase diet. Therefore, when litters were surface-applied to pasture plots, total P in runoff was the same from plots receiving phytase and reduced-P diet litter or no-phytase diet litter. Similarly, Saylor et al. (2001) showed that adding phytase to feed and decreasing inorganic P from 0.43 to 0.33% significantly decreased total P, but not water-extractable P in litter.

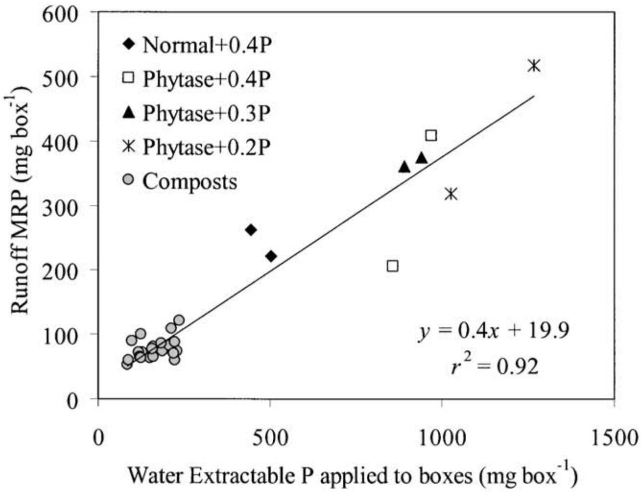

Fig. 3. Relationship between water-extractable P applied to soil boxes in manures and composts and molybdate-reactive phosphorus (MRP) in runoff from the same soil boxes.

DeLaune et al. (2001) applied the litters from the no-phytase normal-P diet and the phytase plus reduced-P diet of Saylor et al. (2001) to tall fescue plots at a rate of 5.6 Mg ha^{-1} and found that molybdate-reactive P concentrations in runoff were greatest from plots with the phytase plus reduced-P litter. However, litters had been deep-stacked for 6 to 8 mo before runoff experiments, which apparently increased water-extractable P in litter from the phytase plus reduced-P ration to concentrations greater than in the no-phytase ration litter.

Effect of Composting Poultry Manure on Phosphorus in Runoff

Total and molybdate-reactive P loads in runoff from boxes with composts were significantly less than P loads in runoff from manure boxes, with a decrease of 60 to 80% for molybdate-reactive P (Table 4). Sharpley and Moyer (2000) reported 42% less molybdate-reactive P leached from composted poultry manure compared with uncomposted manure. Vervoort et al. (1998) applied both poultry litter and composted litter to hayfields and found that molybdate-reactive P in runoff was greater from compost-treated fields. However, more P was applied in compost than in litter to meet crop N needs. Vervoort et al. (1998) did conclude that the composting process created more stable P components and that if litter and compost were land-applied at the same rate of total P, molybdate-reactive P in runoff would probably be greater for litter than for compost. DeLaune et al. (2000) applied both poultry litter and composted litter to tall fescue plots and monitored P in runoff. They found that composting did not significantly affect either molybdate-reactive P or total P in runoff.

Adding Fe and Al before composting did not significantly affect molybdate-reactive P in runoff, compared with unamended compost, but significantly reduced total dissolved P and total P in runoff (Table 4). DeLaune et al. (2000) applied alum-amended poultry litter compost to tall fescue plots and monitored P in runoff. They found that adding alum during the composting process did not significantly affect molybdate-reactive or total P in runoff, even though about five times more Al was present in their compost mixture than in ours. These results suggest that even greater rates of Al addition during the composting process, such as those used by Dao et al. (2001), may be necessary to affect molybdate-reactive P in runoff.

Environmental Implications of the Use of Phytase

The fundamental issue with poultry agriculture and nonpoint-source P pollution is that due to the intensive nature of poultry production, P inputs to farms in feeds and fertilizers often exceed P outputs in crops and animal products. Because most of this P imbalance is in feed inputs, the excess P ultimately ends up in manure, which is typically land-applied and subsequently increases soil P to environmentally hazardous concentrations. The promise of phytase in poultry rations is that an increased availability of native P will decrease the need for supplemental P, thus decreasing farm-scale P imbalance and accumulation of soil P. However, our results and results in the literature show that only if phytase addition to poultry rations is accompanied by substantial reductions in supplemental P (e.g., reductions of 0.2% P or more) will total P in manure decrease, with subsequent reductions in the amount of P farmers must manage, and improvement in the P balance for farms and the region if phytase is widely used. However, if farm-scale P imbalances remain, even with use of phytase and reduced P rations, soil P accumulation and the risk of nonpoint-source P pollution will continue. In these cases, the alternative to soil P accumulation is to export P off the farm through manure sale or utilization in other products, like composts sold off the farm.

Regardless of farm-scale P balances, transfer of P from fields where litter is applied will depend on litter management practices. For long-term time scales (i.e., months and years) for fields where soil P exceeds established environmental thresholds, farmers will probably apply poultry litter according to a P-based management plan. If use of phytase has decreased total P in the litter, farmers can apply more litter to fields without exceeding P loading goals. However, if soil P does not decrease, this will ultimately do little to decrease nonpoint-source P pollution. For fields where soil test P does not exceed environmental thresholds, farmers will probably apply poultry litter according to an N-based management plan. If so, applying phytase-reduced P litter should help slow any accumulation of soil P over time, or even prevent soil P accumulation if P applied in litter does not exceed P uptake in crops.

Another question concerning phytase use is how it may change the speciation of P in manure or litter, and the effect this might have on P speciation in soils and P transfer in runoff. Phytase in poultry feeds will convert the phytate molecule to inorganic orthophosphate and various inositol phosphates, resulting in less phytate and more inorganic P in manure (Table 3; Toor et al., 2003). Phytate molecules are strongly held by soil and are unlikely to be transported in runoff waters, except through direct sediment transport (Turner et al., 2002). Conversion of phytate to inorganic P may increase the potential for P transfer in runoff if the inorganic P is more available to runoff water than the phytate. The research investigating this speciation aspect has reported mixed results for turkey (Maguire et al., 2003) and swine manures (Moore, 2003).

For short-term time scales (i.e., days and weeks), transfer of P from fields where litter is applied will also depend heavily on litter management practices. When poultry litter is surface-applied to soils and left unincorporated, the molybdate-reactive P concentrations in runoff soon after application will be a function of the amount of water-extractable P applied (Fig. 3). Molybdate-reactive P in runoff is of particular concern because it is readily available for algal uptake in surface waters and is therefore a primary contributor to eutrophication (Schindler, 1977; Sonzogni et al., 1982). It is unclear from our results, or results in the literature, that adding phytase and decreasing dietary P in poultry rations will consistently decrease water-extractable P in manure or litter. Although our simulated runoff results represent a worst-case scenario, they indicate that adding phytase to broiler rations may increase molybdate-reactive P in runoff, even when supplemental dietary P is decreased substantially. This is true whether litter is applied according to a P- or N-based management plan. In this case, P transfer in runoff can be minimized only if poultry litter is incorporated into soil, applied at times that avoid immediate runoff, or applied in a landscape position with minimal risk of runoff.

Our data and results in the literature show that composting poultry manure or litter can help stabilize the P in the final product, rendering it less water-extractable and less prone to transfer in runoff. Adding Fe and Al amendments before composting, at rates equal to 2 mol of metal per mole of manure water-extractable P, may not reduce molybdate-reactive P in potential runoff, but can help reduce TP in runoff. Thus, composting could play an important role in the management of poultry waste for the protection of water resources.

CONCLUSIONS

We evaluated the effects of adding phytase and reducing supplemental P in poultry diets on P concentrations in manure and evaluated the effect of composting these manures, with and without additions of Fe or Al, on P concentrations in the final compost product. We then surface-applied manures and composts to soil, subjected them to simulated rainfall, and measured P transfer in runoff. Adding phytase and decreasing P in diets reduced total P but increased water-extractable P in manure, compared with the no-phytase, normal-P diet. Composting reduced both total P and water-extractable P concentrations compared with uncomposted manures, but adding Fe and Al before composting did not consistently change compost P concentrations. Adding phytase and decreasing inorganic P in diets had no significant effect on total P or molybdate-reactive P loads (kg ha^{-1}) in runoff from manures. Composting greatly reduced concentrations and loads of total P and the molybdate-reactive P in runoff. Adding Fe and Al to compost at a 2:1 molar basis of metal to water-extractable P reduced total P loads in runoff but not molybdate-reactive P loads. Overall, molybdate-reactive P in runoff was highly correlated to the amount of water-extractable P applied in manures or composts. The use of phytase may increase manure water-extractable P unless supplemental dietary P is substantially reduced, but phytase appears to have the short-term effect of increasing water-extractable P unless the manure is composted. The final environmental impact of dietary phytase will depend on how dietary phytase and supplemental inorganic P are managed, the management of the farm balance of P inputs versus P outputs, and the manure management practices used for land application of poultry litter.

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